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Rough Surface Propagation Effects at Wallops Island, February–April 1994

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ADMINISTRATIVE INFORMATION

The work described in this Technical Report was performed for Dr. Scott Sandgathe of the Office of Naval Research (ONR 322MM) by the Atmospheric Propagation Branch, D858, SSC San Diego, the Naval Surface Warfare Center Dahlgren Division, and the Lockheed Martin Corporation.

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EXECUTIVE SUMMARY

OBJECTIVE

An unresolved radio propagation modeling problem is the effect of a wind-roughened sea surface on propagation at microwave frequencies in the evaporation duct. The biggest deficiency is the lack of suitable experimental data to validate various existing models. In 1994, the Naval Surface Warfare Center Dahlgren Division (NSWCDD) performed a radio propagation and meteorological measurement program at Wallops Island, Virginia, based on their Microwave Propagation Measurement System (MPMS). MPMS consists of 10 transmitters and 4 receivers using 16 discrete frequencies from 2 to 18 GHz. In the 1994 experiment, a 29.4-km over-water coastal propagation path that was substantially over the horizon for the lowest sited transmitters and receivers was used. In this report, these data are analyzed specifically to investigate the effects of a rough sea surface on propagation in the evaporation duct.

METHOD

The method for examining the MPMS data for rough surface propagation effects was to compute an evaporation duct height and the corresponding vertical refractivity profile for each meteorological observation made near the propagation path. This profile was then input to the MLAYER waveguide propagation model, the transmitter and receiver antenna heights were adjusted by the current tide level, and a modeled propagation loss was computed. The propagation model has the option of using a rough surface reflection coefficient based on an input value of the standard deviation of the sea surface height, also known as the root mean square (rms) bump height. The rms bump height was computed from observed wind speed. Typically, the propagation model was first run for a smooth surface case, then run a second time for the rough surface case. Only the lowest sited transmitter and receiver combination was used in this study since that combination should show the most pronounced rough surface effect. These modeled results were then presented as time or event series plots and accumulated frequency distributions, from which modeled smooth and rough surface propagation loss can be readily compared to observed propagation loss.

CONCLUSION

The Wallops Island 1994 MPMS experiment exhibited only minimal rough surface propagation effects since evaporation duct heights never exceeded 15 m. The high signal levels near free space, originally assumed to be caused by high evaporation duct heights, were apparently caused by propagation mechanisms other than the evaporation duct. When these cases were removed, the Paulus evaporation duct model and MLAYER waveguide propagation model are reasonably good at modeling the observed propagation loss. The rough surface capability of MLAYER seems to be matching observations at the highest frequencies, but a definitive test of this model was not possible since evaporation duct heights never exceeded 15 m.

RECOMMENDATION

A radio and meteorological experiment should be performed to specifically investigate the effects of a rough sea surface on microwave propagation in the evaporation duct. The ideal experiment should have a frequent occurrence of evaporation duct heights greater than 15 m and concurrent wind speeds greater than 10 m/s. The Hawaiian offshore area is expected to have these conditions more than 17 percent of the time. Such an experiment, known as the Rough Evaporation Duct (RED), is

currently being planned for Hawaii in Summer 2001. RED will employ the Research Platform Floating Instrument Platform (R/P FLIP) stationed off the windward side of Oahu to serve as the platform for transmitters at multiple frequencies and for appropriate meteorological measurements. The receivers will be on shore at the Marine Corps Base Hawaii at Kaneohe for a propagation path length of about 30 km.

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INTRODUCTION

The evaporation duct is a propagation mechanism that can significantly increase field strength at frequencies above a few GHz on over-the-horizon, over-water paths. The evaporation duct height describes the strength of the evaporation duct, and there are various methods of computing duct height and the vertical refractivity profile based on sea temperature, air temperature, humidity, and wind speed. A very successful method is known as the Paulus method (Paulus, 1985). The Paulus evaporation duct model used in conjunction with waveguide or parabolic equation models for computing radio propagation loss (or signal strength) has been very successful in modeling statistical propagation effects (Hitney and Vieth, 1990) and reasonably successful in assessing propagation effects versus time (Paulus, 1994; Rogers and Paulus, 1996). For the statistical assessments, the median modeled propagation loss is often within 2 or 3 dB of the median observed loss values when compared to suitable experimental data. However, all cases referred to are for conditions when a roughened sea surface is not expected to affect the propagation loss. Existing propagation models indicate that surface roughness becomes important for frequencies above 10 GHz, duct heights above 15 m, and wind speeds above 10 m/s. However, the application of the Paulus evaporation duct model and a waveguide propagation model (Hitney et al., 1985) to three separate experimental data sets where surface roughness should have been important gave disappointing results (Hitney 1999). In all three cases, the median modeled loss was substantially less than the observed loss. This effort concluded that surface roughness reduces the evaporation duct height or otherwise weakens the strength of the evaporation duct. Another suitable data set for these comparisons would be very desirable.

The Naval Surface Warfare Center Dahlgren Division (NSWCDD) collected experimental data at Wallops Island from February to April 1994. The vertical array of 10 Microwave Propagation Measurement System (MPMS) transmitters was located at Parramore Island and the vertical array of four receivers was located at the southern end of Wallops Island. The path was entirely over water but near and parallel to the coast, and was 29.4 km in length. In this report, only the lowest sited transmitter and receiver were considered, which were located at 1.8 and 5.8 m above mean sea level respectively. Sixteen discrete frequencies between 2 and 18 GHz were employed, which were switched at a 2-Hz rate, allowing all 16 frequencies to be sampled in 8 seconds. The specific frequencies were 2.365, 3.600, 4.365, 5.900, 7.145, 7.530, 8.475, 9.295, 10.400, 12.300, 13.390, 13.570, 14.490, 15.000, 15.900, and 17.350 GHz. Data were collected for all 16 frequencies and all terminal heights, and were recorded in files every 10 minutes. Each file contains 8 minutes of data, with 2 minutes needed for processing. Vertical antenna polarization was used for these measurements. Overall system accuracy in measuring the propagation factor is on the order of 2.6 dB (Queen et al., 1995). A complete description of the site, experimental equipment, and the data collection is provided in Queen et al. (1995). Selected data and comparisons of measured and modeled results from this experiment are provided in Stapleton and Kang (1996).

NSWCDD statistical analysis of the 1994 MPMS data (Stapleton et al., 1998) showed various interesting results, one of which was the occasional occurrence of high signal levels at all the frequencies. Since it was assumed that the evaporation duct was the predominant propagation mechanism on this path, the high signal levels at the lower frequencies seemed to imply that strong evaporation ducts existed during part of the experimental period. As a first step in looking into possible rough surface propagation effects, data from Stapleton et al. (1998) were re-displayed as a propagation factor exceeding 50, 10, 5, and 0 percent of the time versus frequency. Figure 1 provides

the results. Propagation factors greater than free space (0 dB) occurred occasionally at all frequencies. Maximum propagation factors exceeded 10 dB at most frequencies and 15 dB at a few frequencies. Figure 1 also includes the modeled propagation factor that is never exceeded (i.e., the maximum propagation factor). This model is based on vertical profiles of radio refractivity from Paulus (1985) and the MLAYER model (Hitney et al., 1985) for the geometry of the 1994 experiment. However, specific meteorological data were not needed since the modeled curve of figure 1 only depends on the maximum propagation factor that is possible at any duct height up to 40 m (a value rarely exceeded in any condition) for each frequency. The modeled and observed maximum propagation factor curves are within 10 dB at all frequencies and within 5 dB at most frequencies. Based on these curves, it was decided that strong evaporation ducts were most likely present part of the time. As will be pointed out in a later section, this assumption was false.

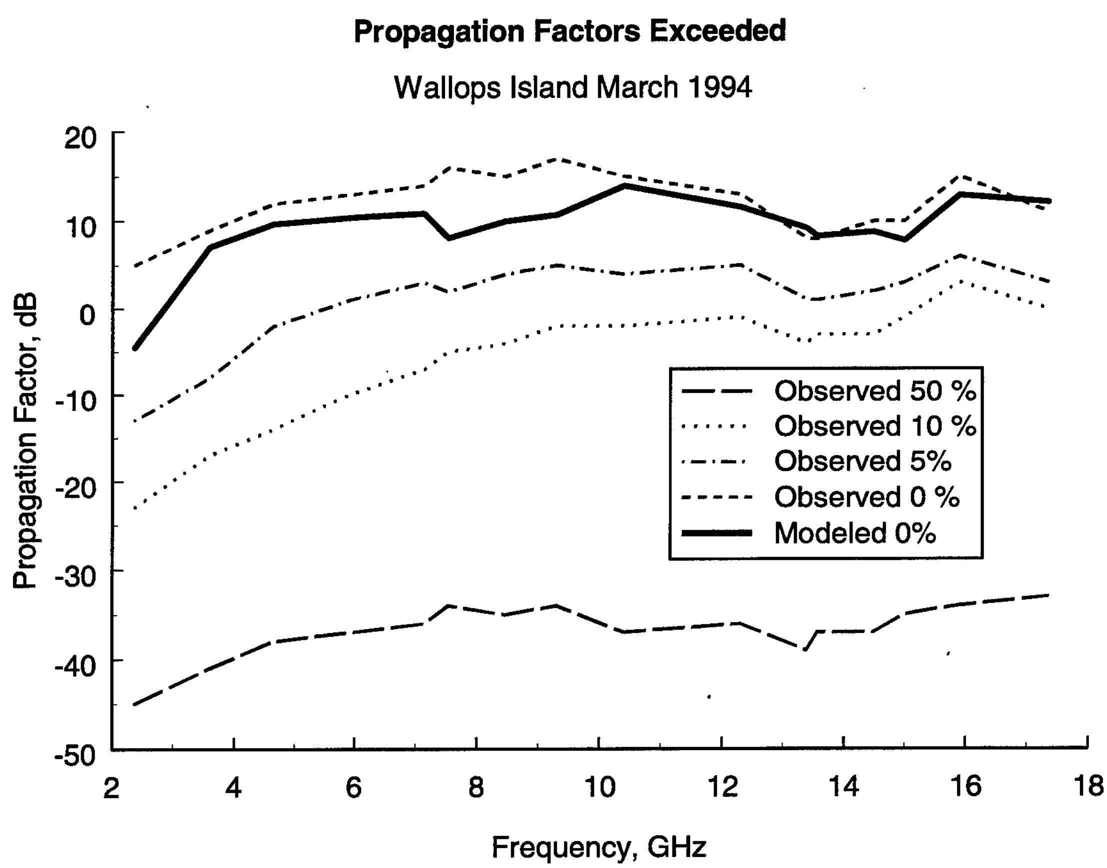

Figure 1. Propagation factors exceeded at selected percentages versus frequency.

Various meteorological support measurements were made in conjunction with the MPMS measurements. NSWCDD installed and operated a meteorological van at the receiver site that made local measurements and monitored two buoys that were located near the center of the propagation path. The local measurements were made using a 30-m meteorological tower with a fixed array of 10 sensors and another 30-m tower with a single moving sensor package. The primary buoy was an Endeco waverider buoy that included measurements of sea and air temperature, relative humidity, wind speed and direction, and wave height. There was also a second meteorological buoy that

included a vertical array of temperature sensors used to assess infrared propagation effects. The Applied Physics Laboratory (APL) of Johns Hopkins University provided a research boat, *Chessie*. Meteorological measurements were made aboard the boat at various heights and very near the sea surface with a towed sled. APL also made meteorological measurements from a helicopter that flew sawtooth patterns from near the surface to about a 500-m altitude. Both *Chessie* and the helicopter only operated on selected days of the operation. In addition, a NASA ground station also provided meteorological data. A summary of these data is provided in Queen et al. (1995). In this report, only the Endeco buoy and *Chessie* boat data are considered because they were deemed the most complete and appropriate as inputs to the Paulus evaporation duct model. The Endeco data were recorded every 10 minutes throughout the experiment and the *Chessie* data were recorded every 5 minutes during selected periods of the experiment. More detail will be given on both data sets in the following sections. However, an early cursory examination of the Endeco data showed that wind speeds did exceed the required 10 m/s for some time periods, so rough surface effects should have been important at the higher frequencies if the duct heights were high enough.

Based on the assumption that high duct heights and wind speeds existed, it was decided to undertake a thorough examination of the 1994 MPMS data for rough surface effects. However, since only a limited time-series analysis had been performed on these data previously, there was a lot of work involved in organizing and processing the MPMS and meteorological data and putting them into a form ready to analyze. NSWCDD and the Lockheed Martin Corporation performed this part of the task for SSC San Diego. The MPMS data had to be quality controlled and matched to the Endeco and *Chessie* data samples. The propagation factor had to be computed and averaged (as an average power) and written to a file that could be easily matched to the appropriate meteorological data. Also, the meteorological data needed to be quality controlled, corrected or edited as appropriate, and written to files. The next section describes these tasks and the resultant files.

DATA PREPARATION

FILES AND FILE FORMATS

Six files were delivered by NSWCDD to SSC San Diego for this project: two MPMS propagation factor MATLAB files, mpms_chessie_data.mat and mpms_endeco_data.mat, and two meteorological ASCII data files, chessie.asc and endeco.asc, and two copies of the original data, ch94.asc and endeco94.asc.

MPMS PROPAGATION FACTOR FOR THE ENDECO MET. DATA FILE: MPMS_ENDECO_DATA.MAT

The file, mpms_endeco_data.mat, contains the following MATLAB variables.

Variable name	Size	Description
freq	16	Frequencies in GHz
mpms_pf	4 x 10 x 16 x 2694	Propagation factor in dB per RX, per TX, per Frequency, per Endeco data sample
rx_height	4	Receiver heights above mean sea level in feet
tide_ht	2694	Tide height in feet
tx_height	10	Transmitter heights above mean sea level in feet

mpms_pf. MPMS data were collected by examining each MPMS data file in succession and determining if there were any Endeco data points for which data from this MPMS data file could be used within a window 3 minutes on either side of the MPMS sample (i.e., if the MPMS data file ran from 1:15 to 1:23, then possibly these data could be used with Endeco points from 1:12 to 1:26). The MPMS data points were averaged as power and reconverted to propagation factor in dB. Points where no data could be found remained invalid and were indicated by NaN (Not a Number). There were 1405 such points of 2694 total points. MPMS files that appeared to contain bad data were not included. Bad data were determined by visual inspection of previously compiled 1994 MPMS color propagation factor images.

tide_ht. When valid MPMS data were found, the tide height was interpolated from the Tide height file to the time of the Endeco data. Remaining NaN data normally indicate that no MPMS data were available for the corresponding Endeco data point. The original tide height data appeared to be complete.

MPMS PROPAGATION FACTOR FOR THE CHESSIE MET. DATA FILE: MPMS_CHESSIE_DATA.MAT

The file mpms_chessie_data.mat contains the same five MATLAB variables collected in the same manner as described above for the Endeco data, but for the 1147 Chessie data points (759 of which contain MPMS data).

CHESSIE METEOROLOGICAL DATA

There are two files containing *Chessie* meteorological data. The file ch94.asc contains the original uncorrected (or unedited) meteorological data. The file chessie.asc contains the corrected (or edited) meteorological data.

The file, ch94.asc, contains the complete original *Chessie* data set. The original single measurement ASCII files were concatenated into one file where each measurement is a single line. No error checking was done on these data. The file, ch94.asc, contains 1147 data points. The data in the file chessie.asc are the same 1147 data points in the same 23 columns as the data in ch94.asc, except suspect data have been changed to NaN.

Each line of both Chessie files contains the following columns:

Col	Parameters
1	Month
2	Day
3	Year
4	Hour (UTC)
5	Minute
6	Latitude (DEG)
7	Longitude (DEG)
8	Average wind speed (KNOTS)
9	Wind direction (DEG, TRUE)
10	Water temperature (C)
11	Average 6-meter pressure (MILLIBARS)
12	0.02-meter air temperature (C)
13	0.02-meter humidity (%)
14	1-meter air temperature (C)
15	1-meter humidity (%)
16	2-meter air temperature (C)
17	2-meter humidity (%)
18	Average 6-meter air temperature (C)
19	Average 6-meter humidity (%)
20	10-meter air temperature (C)
21	10-meter humidity (%)

22	18-meter air temperature (C)
23	18-meter humidity (%)

ENDECO METEOROLOGICAL DATA

There are two files containing Endeco meteorological data. The file endeco94.asc contains the original uncorrected (unedited) meteorological data. The file endeco.asc contains the corrected (edited) meteorological data.

The file endeco94.asc contains the complete original Endeco data set. It was produced in 1994 by concatenating the original single measurement ASCII files into one file where each measurement is a single line. This file was our starting point for producing the corrected (edited) Endeco data file. The file endeco94.asc contains 2694 data points. The data in file endeco.asc are the same 2694 data points in the same 15 columns as the data in endeco94.asc, except suspect data have been changed to NaN.

Each line of both Endeco files contains the following columns:

Col	Parameters
1	Month
2	Day
3	Year
4	Hour (UTC)
5	Minute
6	Second
7	Buoy significant wave height (H1/3, meters)
8	Buoy wave direction (maximum energy direction, degrees)
9	Buoy wind speed (knots)
10	Buoy wind direction (degrees)
11	Buoy air temperature (C)
12	Buoy water temperature (C)
13	Buoy relative humidity (%)
14	Buoy sphere temperature (C)
15	Buoy battery voltage (volts)

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DATA ANALYSIS

The concept for analyzing the MPMS data was to use the Paulus method to compute a duct height and the corresponding vertical refractivity profile for each meteorological data point from either the *Chessie* or Endeco file. This profile was then input to MLAYER, the transmitter and receiver antenna heights were adjusted by the current tide level, and a modeled propagation loss was computed. MLAYER has the option of using the Miller-Brown (Miller et. al., 1984) rough surface reflection coefficient model based on an input value of the standard deviation of the sea surface height, also known as the root mean square (rms) bump height. The rms bump height can either be computed from observed significant wave height or from wind speed (Hitney et al., 1985). The Chessie data did not include wave height and, although the Endeco data did include wave height, it was sparse, so the wind speed option was used to compute the rms bump height for MLAYER. Typically, MLAYER was first run for a smooth surface case, then run a second time for the rough surface case. Only the lowest sited transmitter and receiver combination was used in this study since that combination should show the most pronounced rough surface effect. An ASCII file was then generated for each frequency with the Julian day (as a decimal fraction to four places), wave height, wind speed, the sea and air temperatures, the relative humidity, duct height, smooth modeled loss, rough modeled loss, and observed loss (all loss values in dB). These files could then be used as the basis for plotted time or event series or to generate frequency distributions of the various quantities.

The *Chessie* data were analyzed first, since all of the meteorological data appeared complete for the application of the Paulus evaporation duct model. Only the highest frequency of 17.350 GHz was considered. There were 300 5-minute samples for which valid meteorological and radio data existed. Figure 2 shows the meteorological data and resultant duct height plotted versus event number for the Chessie data measured at 6 m above sea level. These data are monotonic but not continuous in time, as the abrupt changes in the parameters indicate. Note the condition for rough surface effects of a duct height greater than 15 m and a concurrent wind speed greater than 10 m/s never existed. In Figure 2, only every second event point is plotted for the air and sea temperatures for clarity. Figure 3 shows the propagation loss at 17.350 GHz plotted versus the same event numbers. The MLAYER model results (open circles) in the upper panel were computed for smooth surface conditions (i.e., zero wind speed), and in the lower panel they were computed for rough surface conditions based on the wind speed measured on *Chessie*. Many of the *Chessie* samples were taken at locations 10 to 20 km removed from the center of the propagation path, and sometimes *Chessie* was in or near the harbor, about 25 km from the center of the propagation path. In spite of this limitation, the overall comparison between modeled and observed losses is still fair. There are some cases where the rough surface model matches the observations much better, such as events 1 through 18, but with others, such as events 290 to 300, the opposite is true. Figure 4 shows the accumulated frequency distribution of propagation loss for the smooth and rough model and the observed data. Both models match the observed distribution fairly well, within about 5 dB at all percentages. At the upper percentages the rough surface model is much closer to the observed data, but it must be remembered that overall estimated system accuracy of 2.6 dB is on the same order as the difference between the smooth and rough surface models. The sharp drop in the observed distribution between 185 and 190 dB is because of system threshold considerations. The rms error is 9.6 and 9.3 dB for the smooth and rough surface models respectively. The bias (difference between the modeled and observed medians) is -5.9 and -4.0 dB for the smooth and rough surface models respectively.

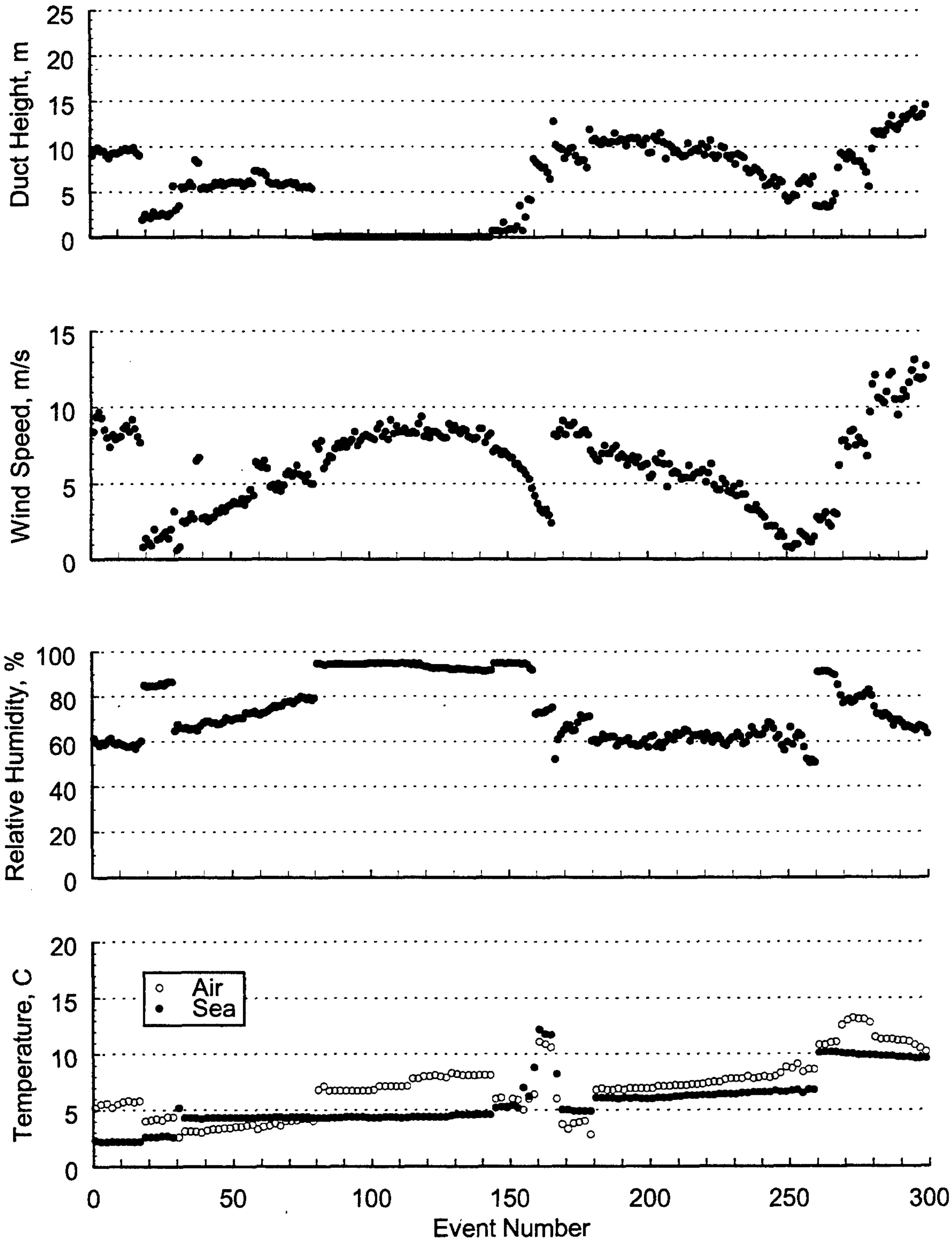

Figure 2. Meteorological data recorded by research boat, *Chessie*, and evaporation duct height computed with Paulus model.

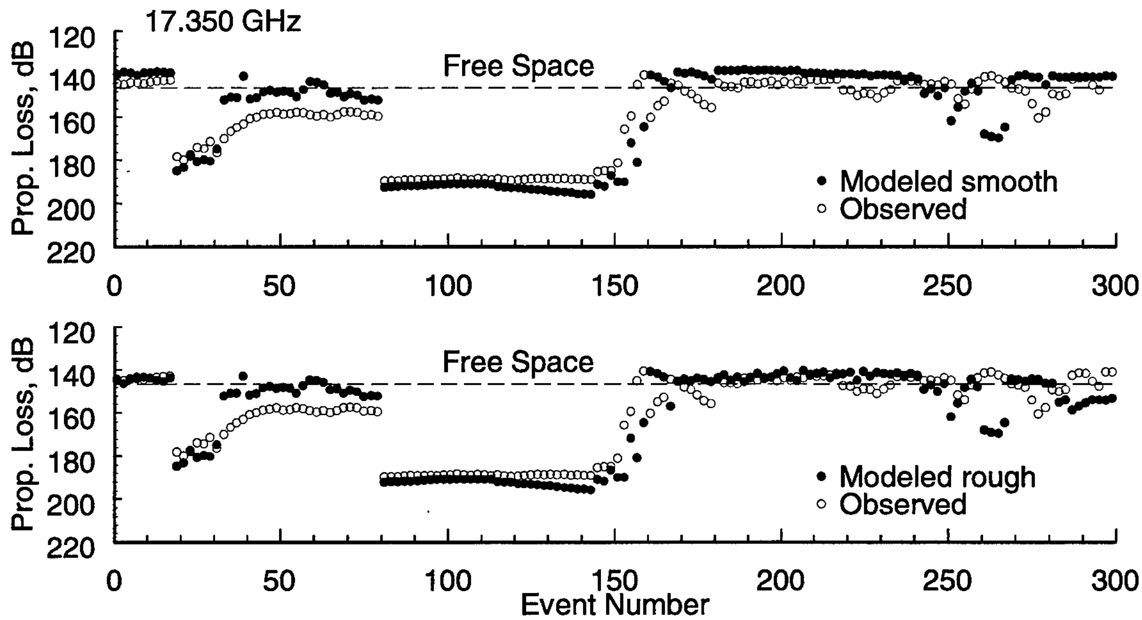

Figure 3. Propagation loss derived from *Chessie* meteorological data versus event number for modeled smooth surface (upper) and modeled rough surface (lower) cases compared to observed propagation loss.

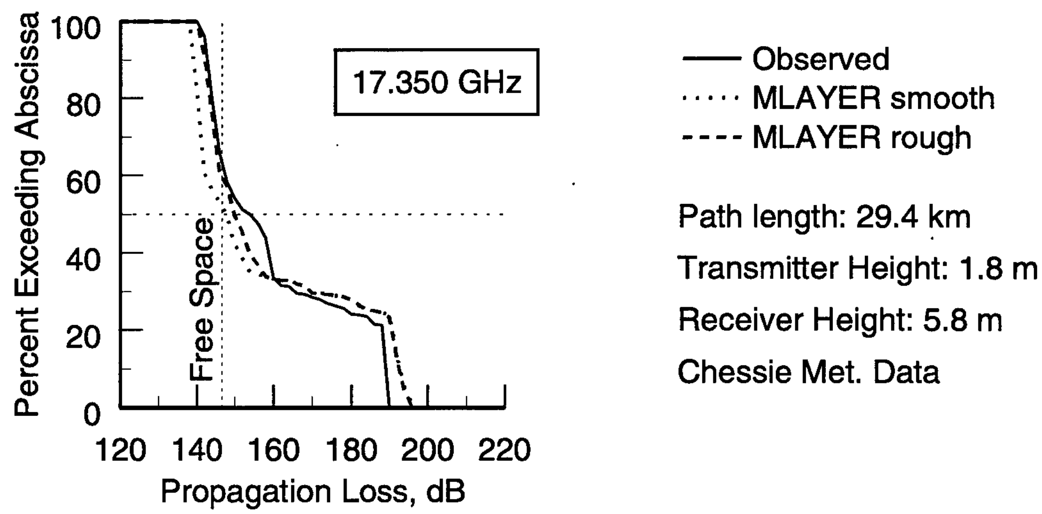

Figure 4. Accumulated frequency distributions of propagation loss for modeled smooth surface (dots), modeled rough surface (dashes), and observed (solid). Modeled results are derived from *Chessie* meteorological data.

The next step was to use the Endeco waverider buoy measurements to drive the Paulus model. The Endeco data should be the best data source since it was located near the center of the propagation path and data were collected throughout the measurement period. However, the sea temperature probe failed on the buoy after only a few days of operation, so some method was needed to overcome this limitation. Sea temperatures from *Chessie* were selected for those days when *Chessie* was close to the buoy. These temperatures and the last valid temperature recorded on the buoy at Julian day 42.0417 (11 Feb 1999 0100 UTC) were used to derive a quadratic equation least-squares fit that could be used for extrapolating sea temperature throughout the measurement period. The derived formula is

$$T_s = 6.608 - 0.2086J + 0.002516J^2, \tag{1}$$

where T_s is the sea temperature and J is the Julian day. Figure 5 shows the plots of sea and air temperatures, relative humidity, wind speed, and Paulus duct height versus Julian day. On the temperature plots, only every third point is plotted for clarity while for the other plots, all 1173 samples are plotted. The maximum duct height was 15 m and the wind speed occasionally exceeded 10 m/s, similar to the *Chessie* data. Thus, again we expect that rough surface effects will not be pronounced. The impact of using extrapolated sea temperature from *Chessie* for these data is not thought to be severe, since the entire data set was rerun assuming neutral conditions (sea temperature was set equal to air temperature) and the resulting duct heights were very much the same as those shown in figure 5. The following results probably would have been similar for the neutral model, but an extrapolated sea temperature from equation (1) seemed more realistic.

Figure 6 shows the results of modeling derived from the Endeco data for a smooth surface at five selected frequencies: 2.365, 5.900, 10.400, 13.570, and 17.350 GHz. The solid circles show the modeled results and the open circles show the observed data. All 1173 points are included. The modeled and observed data match quite well in most places. However, for the lowest frequency, there are a few periods where the observed propagation loss is much less than the modeled loss. In these periods, the loss values are often comparable to or less than the free space loss. These cases are most likely attributable to propagation mechanisms other than the evaporation duct, namely surface or surface-based ducts (Hitney et al., 1985). At the higher frequencies, it is hard to distinguish these effects from the evaporation duct effects because the propagation loss levels are often comparable, but this is not the case at the lowest frequency. Thus, the data set was modified to remove selected time periods determined by manual inspection of the modeled and observed losses. As table 1 shows, this operation removed five time periods. The periods selected were chosen based on the 2.365 GHz loss levels near free space and the times before and after where propagation mechanisms other than the evaporation duct were suspected. Also, if the loss fluctuated greatly from near free space to much greater values, these periods were also selected. The five periods comprise 252 observations or about 21 percent of the total of 1173 observations. Probably about half of the 252 were cases were in fact evaporation duct cases, but these have been removed because there is no clear way to identify them. The resulting reduced data set consists of 921 samples.

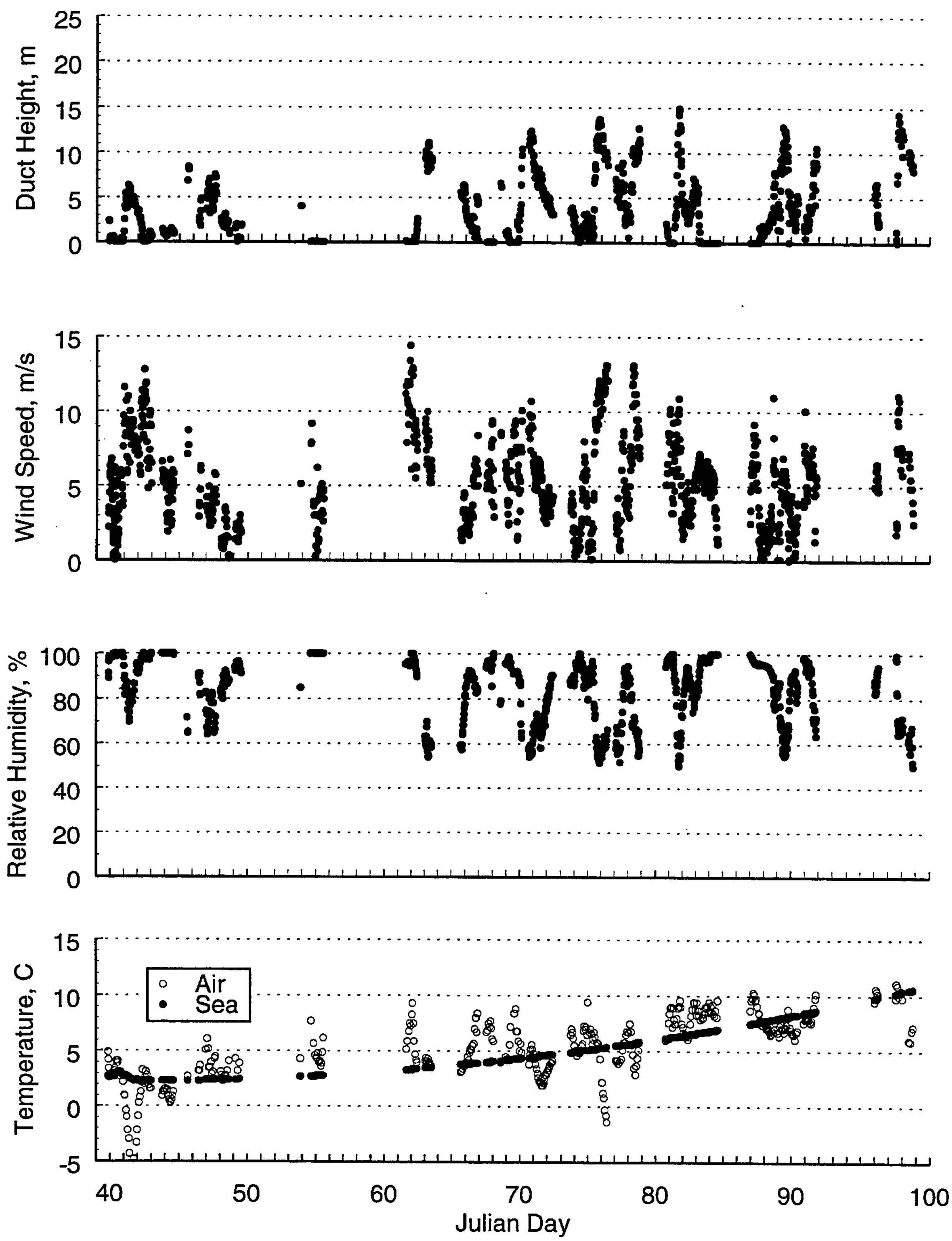

Figure 5. Meteorological data collected on Endeco buoy and duct height from Paulus model versus Julian day. Sea temperature was extrapolated based mostly on *Chessie* boat measurements.

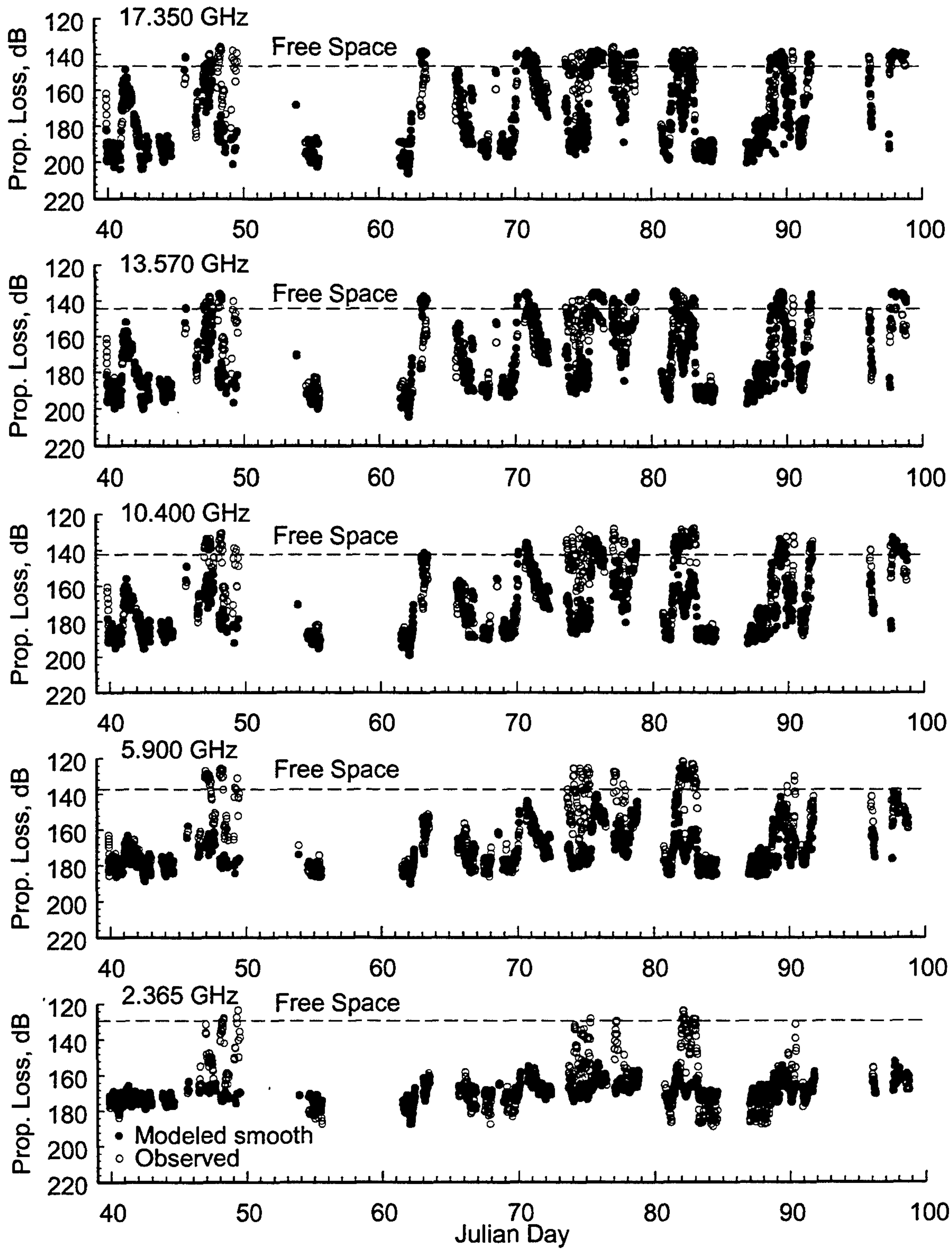

Figure 6. Smooth surface modeled and observed propagation loss versus Julian day for five frequencies. Modeled results are derived from Endeco meteorological data.

Table 1. Periods removed from observations based on Endeco data.

Period Number	Julian Day Start	Julian Day Stop
1	46.5417	49.5417
2	73.7292	75.3750
3	77.1042	77.9792
4	82.0000	83.2083
5	89.8958	90.5000

Figure 7 shows the smooth surface modeled results for the five frequencies for the reduced data set in the same format as figure 6. The match overall between modeled and observed is very good at all frequencies, and is much better than figure 6. Figure 8 shows the rough surface modeled results for the reduced data set in the same format as figures 6 and 7. Overall, there is very little difference between the smooth and rough surface modeled results. Table 2 shows the correlation coefficient, rms error, and bias for the five frequencies of figures 6 through 8. Reducing the data set was clearly an improvement, as is seen from the significantly increased correlation coefficients of figure 7 compared to figure 6. The correlation coefficients for the rough surface model in figure 8 were nearly the same (actually a little less at the highest frequency) compared to the smooth model of figure 7. It is difficult to see any difference between figures 7 and 8.

Figure 9 shows the accumulated frequency distributions of propagation loss for the five frequencies based on the reduced data set for the smooth surface model, rough surface model, and observations. For all five frequencies, the match between the modeled and observed data was very good, which implied that the Paulus duct height model and the MLAYER propagation model were both performing well. The only differences between the smooth and rough surface models occurred at the two highest frequencies at the higher percentages (the smooth and rough surface model distributions are virtually the same for the lower frequencies). For the two highest frequencies, the rough model was a closer match to the observed than the smooth model, but the improvement was only a few dB.

Table 2. Descriptive statistics for figure 6 (original data set, smooth surface model), figure 7 (reduced data set, smooth surface model), and figure 8 (reduced data set, rough surface model).

Frequency (GHz)	Correlation Coefficient			RMS Error (dB)			Bias (dB)		
	Fig. 6	Fig. 7	Fig. 8	Fig. 6	Fig. 7	Fig. 8	Fig. 6	Fig. 7	Fig. 8
2.365	0.37	0.71	0.71	12.3	6.2	6.3	-0.1	-3.1	-3.1
5.900	0.52	0.84	0.84	16.6	7.0	6.9	7.2	1.2	1.1
10.400	0.71	0.90	0.90	15.5	8.4	8.1	7.2	-4.3	-4.3
13.570	0.70	0.89	0.89	14.8	10.6	9.7	7.2	-3.4	-3.5
17.350	0.76	0.90	0.88	14.9	10.1	9.7	10.2	-5.9	-4.0

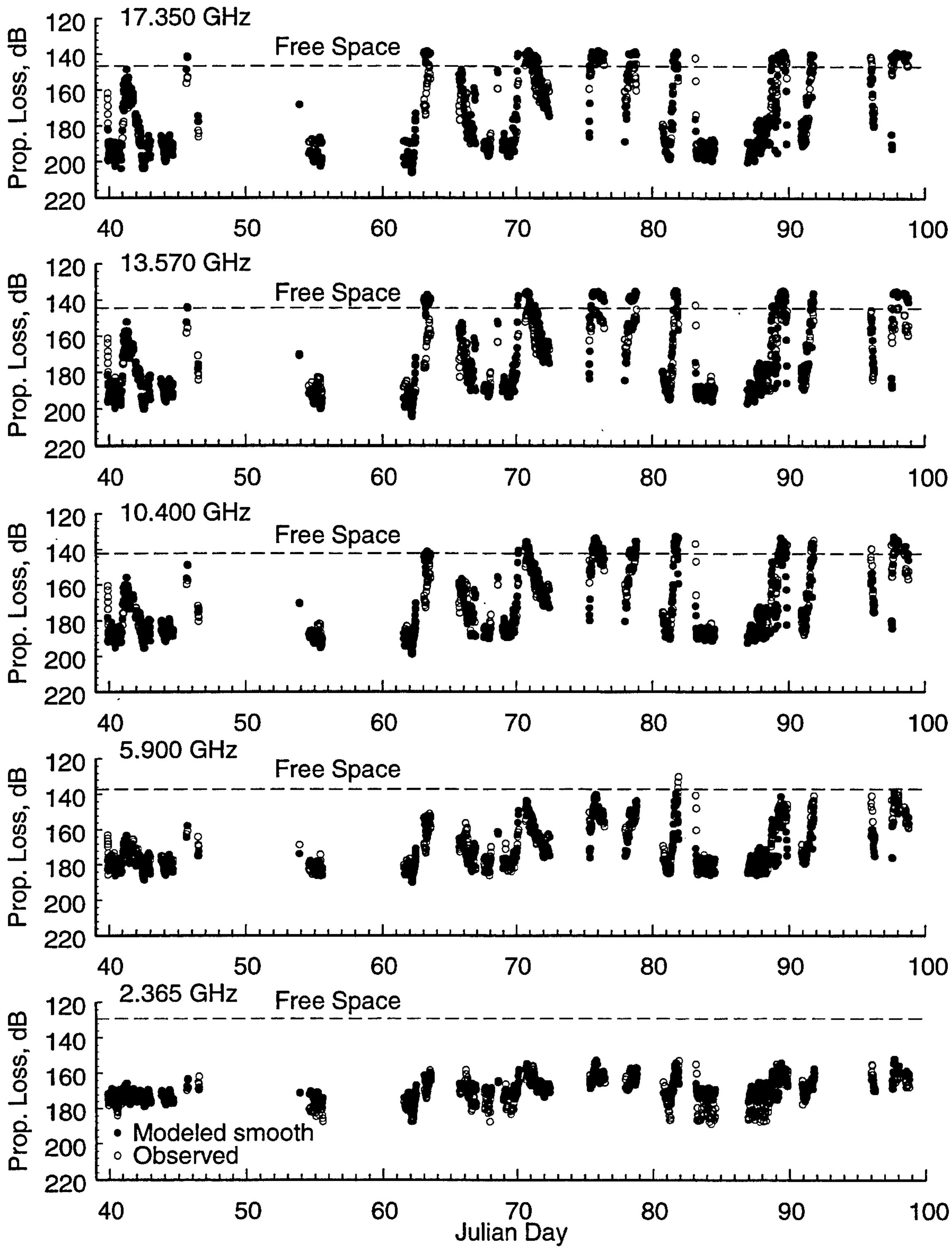

Figure 7. Smooth surface modeled and observed propagation loss versus Julian day for five frequencies. Modeled results are derived from Endeco meteorological data using the reduced data set.

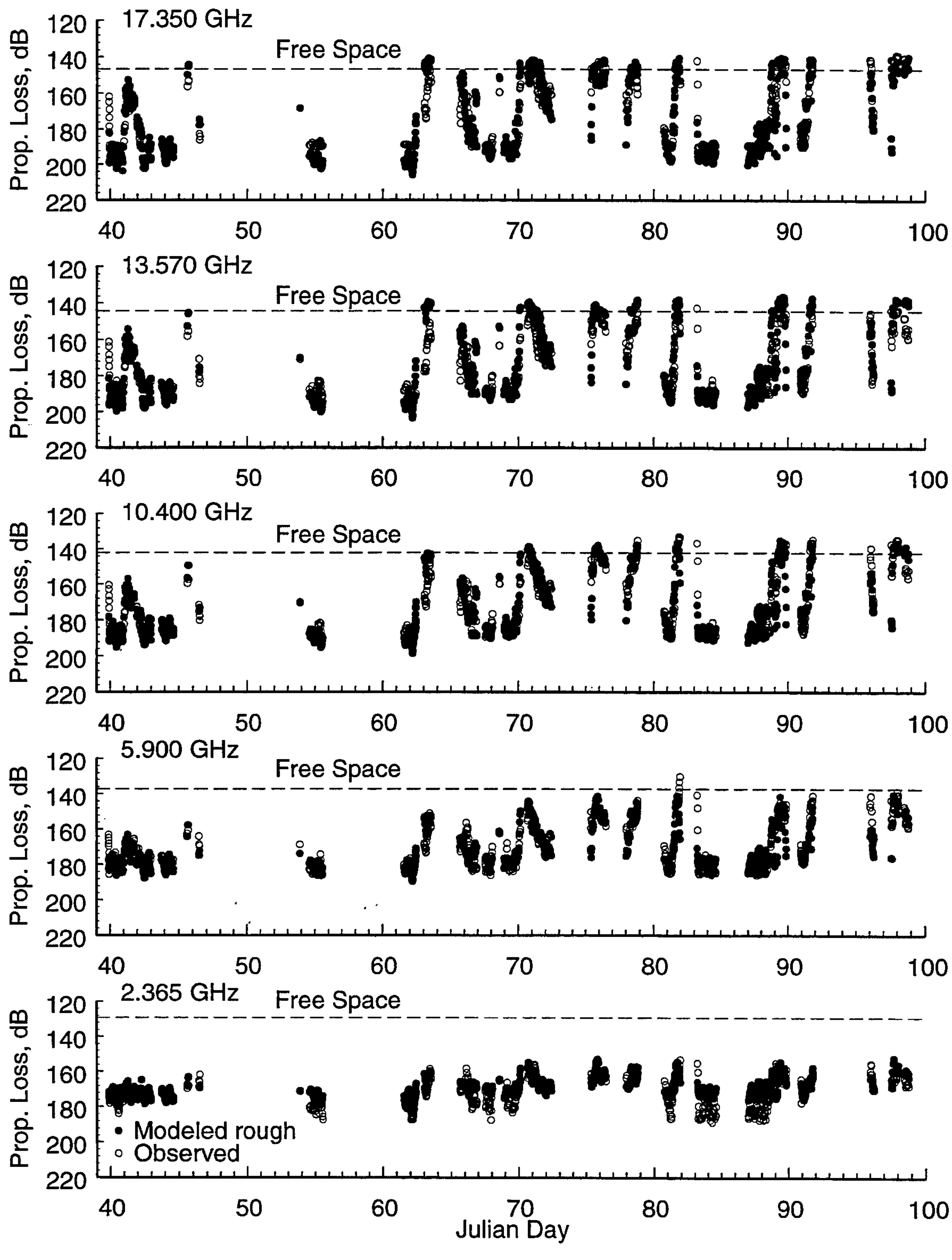

Figure 8. Rough surface modeled and observed propagation loss versus Julian day for five frequencies. Modeled results are derived from Endeco meteorological data using the reduced data set.

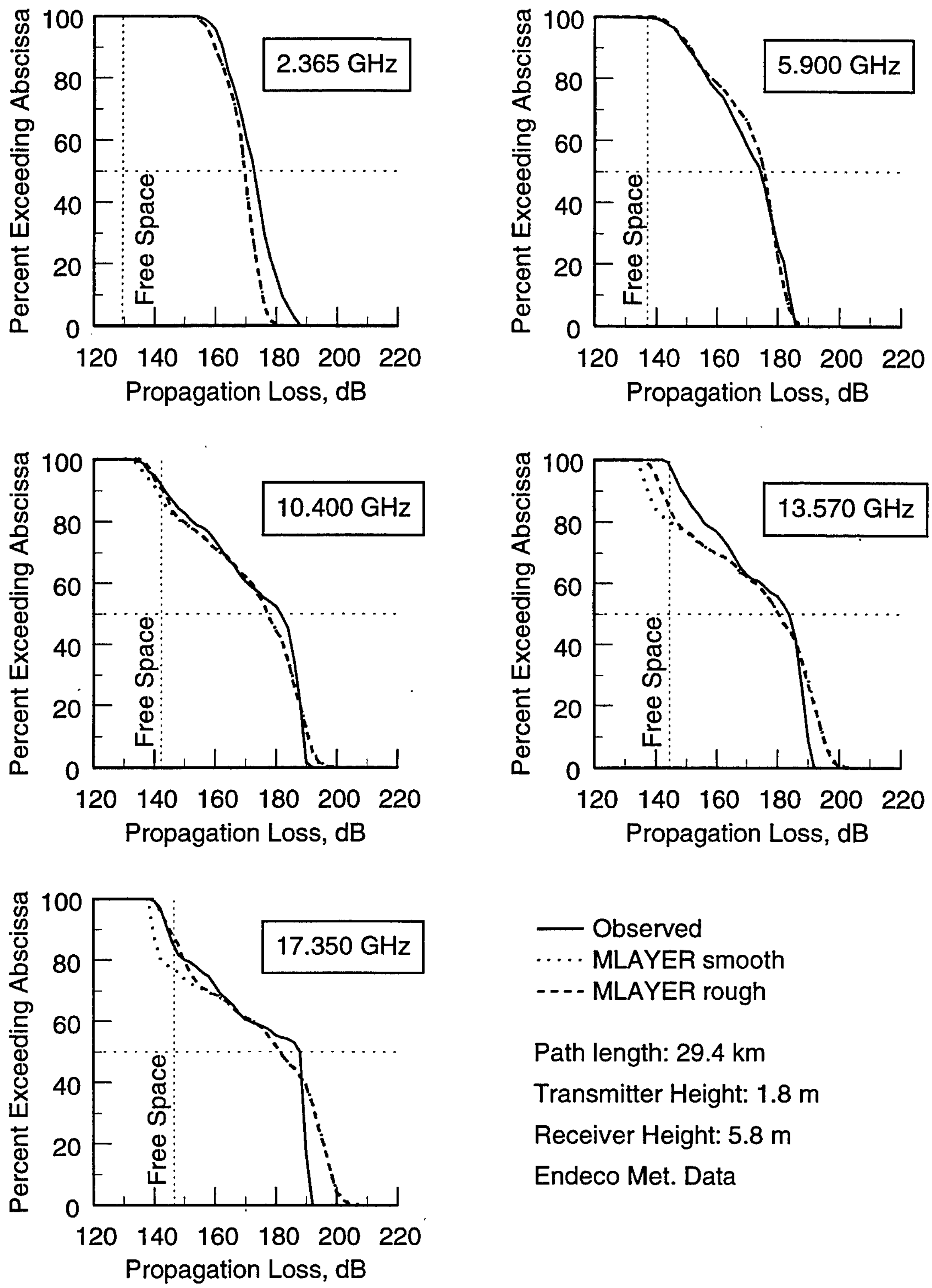

Figure 9. Accumulated frequency distributions of smooth surface modeled (dots), rough surface modeled (dashes), and observed propagation loss (solid) for five frequencies. Modeled results are derived from Endeco meteorological data using reduced data set.

CONCLUSIONS

The Wallops Island 1994 MPMS experiment exhibited only minimal rough surface propagation effects since evaporation duct heights never exceeded 15 m. The high signal levels near free space, originally assumed to be caused by high evaporation duct heights, were apparently caused by propagation mechanisms other than the evaporation duct. When these cases were removed, the Paulus evaporation duct model and MLAYER waveguide propagation model are reasonably good at modeling the observed propagation loss. The rough surface capability of MLAYER seems to be matching observations at the highest frequencies, but a definitive test of this model was not possible since evaporation duct heights never exceeded 15 m.

RECOMMENDATION

A radio and meteorological experiment should be performed to specifically investigate the effects of a rough sea surface on microwave propagation in the evaporation duct. The ideal experiment should have a frequent occurrence of evaporation duct heights greater than 15 m and concurrent wind speeds greater than 10 m/s. The Hawaiian offshore area is expected to have these conditions more than 17 percent of the time. Such an experiment, known as the Rough Evaporation Duct (RED), is currently being planned for Hawaii in Summer 2001. RED will employ the Research Platform Floating Instrument Platform (R/P FLIP) stationed off the windward side of Oahu to serve as the platform for transmitters at multiple frequencies and for appropriate meteorological measurements. The receivers will be on shore at the Marine Corps Base Hawaii at Kaneohe for a propagation path length of about 30 km.

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An unresolved radio propagation modeling problem is the effect of a wind-roughened sea surface on propagation at microwave frequencies in the evaporation duct. The biggest deficiency is the lack of suitable experimental data to validate various existing models. In 1994, the Naval Surface Warfare Center Dahlgren Division (NSWCDD) performed a radio propagation and meteorological measurement program at Wallops Island, Virginia, based on their Microwave Propagation Measurement System (MPMS). MPMS consists of 10 transmitters and 4 receivers using 16 discrete frequencies from 2 to 18 GHz. In the 1994 experiement, a 29.4-km over-water coastal propagation path that was over the horizon for the lowest sited transmitters and receivers was used,. In this report, these data are analyzed specifically to investigate the effects of a rough sea surface on propagation in the evaporation duct.

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